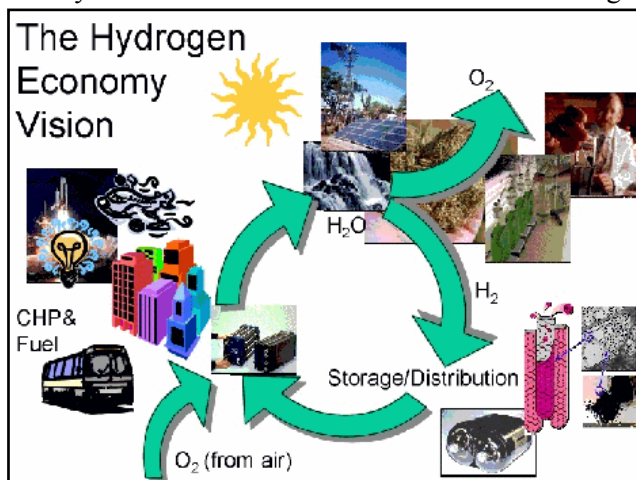


# Hydrogen

## Technology Description

Similar to electricity, hydrogen can be produced from many sources, including fossil fuels, renewable resources, and nuclear energy. Hydrogen and electricity can be converted from one to the other using electrolyzers (electricity to hydrogen) and fuel cells (hydrogen to electricity). Hydrogen is an effective energy storage medium, particularly for distributed generation. When hydrogen produced from renewable resources is used in fuel cell vehicles or power devices, there are very few emissions—the major byproduct is water. With improved conventional energy conversion and carbon-capture technologies, hydrogen from fossil resources can be used efficiently with few emissions.

The Hydrogen Economy vision is based on a clean and elegant cycle: separate water into hydrogen and oxygen using renewable or nuclear energy, or fossil resources with carbon sequestration. Use the hydrogen to power a fuel cell, internal combustion engine, or turbine, where hydrogen and oxygen (from air) recombine to produce electrical energy, heat, and water to complete the cycle. This process produces no particulates, no carbon dioxide, and no pollution.



### System Concepts

- Hydrogen made via electrolysis from excess nuclear or renewable energy can be used as a sustainable transportation fuel or stored to meet peak-power demand. It also can be used as a feedstock in chemical processes.
- Hydrogen produced by decarbonization of fossil fuels followed by sequestration of the carbon can enable the continued, clean use of fossil fuels during the transition to a carbon-free Hydrogen Economy.
- A hydrogen system is comprised of production, storage, distribution, and use.
- A fuel cell works like a battery but does not run down or need recharging. It will produce electricity and heat as long as fuel (hydrogen) is supplied. A fuel cell consists of two electrodes—a negative electrode (or anode) and a positive electrode (or cathode)—sandwiched around an electrolyte. Hydrogen is fed to the anode, and oxygen is fed to the cathode. Activated by a catalyst, hydrogen atoms separate into protons and electrons, which take different paths to the cathode. The electrons go through an external circuit, creating a flow of electricity. The protons migrate through the electrolyte to the cathode, where they reunite with oxygen and the electrons to produce water and heat. Fuel cells can be used to power vehicles, or to provide electricity and heat to buildings.

### Representative Technologies

#### *Hydrogen production*

- Thermochemical conversion of fossil fuels, biomass, and wastes to produce hydrogen and  $CO_2$  with the  $CO_2$  available for sequestration (large-scale steam methane reforming is widely commercialized)
- Renewable (wind, solar, geothermal, hydro) and nuclear electricity converted to hydrogen by electrolysis of water (commercially available electrolyzers supply a small but important part of the super-high-purity hydrogen market)
- Photoelectrochemical and photobiological processes for direct production of hydrogen from sunlight and water.

#### *Hydrogen storage*

- Pressurized gas and cryogenic liquid (commercial today)
- Higher pressure (10,000 psi), carbon-wrapped conformable gas cylinders
- Cryogenic gas
- Chemically bound as metal or chemical hydrides or physically adsorbed on carbon nanostructures

#### *Hydrogen distribution*

- By pipeline (relatively significant pipeline networks exist in industrial areas of the Gulf Coast region, and near Chicago)
- By decentralized or point-of-use production using natural gas or electricity
- By truck (liquid and compressed hydrogen delivery is practiced commercially)

#### *Hydrogen use*

- Transportation sector: internal combustion engines or fuel cells to power vehicles with electric power trains. Potential long-term use as an aviation fuel and in marine applications
- Industrial sector: ammonia production, reductant in metal production, hydrotreating of crude oils, hydrogenation of oils in the food industry, reducing agent in electronics industry, etc.
- Buildings sector: combined heat, power, and fuel applications using fuel cells
- Power sector: fuel cells, gas turbines, generators for distributed power generation

### **Technology Applications**

• In the United States, nearly all of the hydrogen used as a chemical (i.e. for petroleum refining and upgrading, ammonia production) is produced from natural gas. The current main use of hydrogen as a fuel is by NASA to propel rockets.

• Hydrogen's potential use in fuel and energy applications includes powering vehicles, running turbines or fuel cells to produce electricity, and generating heat and electricity for buildings. The current focus is on hydrogen's use in fuel cells.

The primary fuel cell technologies under development are:

*Phosphoric acid fuel cell (PAFC)* - A phosphoric acid fuel cell (PAFC) consists of an anode and a cathode made of a finely dispersed platinum catalyst on carbon paper, and a silicon carbide matrix that holds the phosphoric acid electrolyte. This is the most commercially developed type of fuel cell and is being used in hotels, hospitals, and office buildings. More than 250 commercial units exist in 19 countries on five continents. This fuel cell also can be used in large vehicles, such as buses.

*Proton-exchange membrane (PEM)* - The proton-exchange membrane (PEM) fuel cell uses a fluorocarbon ion exchange with a polymeric membrane as the electrolyte. The PEM cell appears to be more adaptable to automobile use than the PAFC type of cell. These cells operate at relatively low temperatures and can vary their output to meet shifting power demands. These cells are the best candidates for light-duty vehicles, for buildings, and much smaller applications.

*Solid oxide fuel cells (SOFC)* - Solid oxide fuel cells (SOFC) currently under development use a thin layer of zirconium oxide as a solid ceramic electrolyte, and include a lanthanum manganate cathode and a nickel-zirconia anode. This is a promising option for high-powered applications, such as industrial uses or central electricity generating stations.

*Direct-methanol fuel cell (DMFC)* - A relatively new member of the fuel cell family, the direct-methanol fuel cell (DMFC) is similar to the PEM cell in that it uses a polymer membrane as an electrolyte. However, a catalyst on the DMFC anode draws hydrogen from liquid methanol, eliminating the need for a fuel reformer.

*Molten carbonate fuel cell (MCFC)* - The molten carbonate fuel cell uses a molten carbonate salt as the electrolyte. It has the potential to be fueled with coal-derived fuel gases or natural gas.

*Alkaline fuel cell* - The alkaline fuel cell uses an alkaline electrolyte such as potassium hydroxide. Originally used by NASA on missions, it is now finding applications in hydrogen-powered vehicles.

*Regenerative or Reversible Fuel Cells* - This special class of fuel cells produces electricity from hydrogen and oxygen, but can be reversed and powered with electricity to produce hydrogen and oxygen.

### Current Status

- Currently, 48% of the worldwide production of hydrogen is via large-scale steam reforming of natural gas. Today, we safely use about 90 billion cubic meters (3.2 trillion cubic feet) of hydrogen yearly.
- Direct conversion of sunlight to hydrogen using a semiconductor-based photoelectrochemical cell was recently demonstrated at 12.4% efficiency.
- Hydrogen technologies are in various stages of development across the system:  
*Production* - Hydrogen production from conventional fossil-fuel feedstocks is commercial, and results in significant CO<sub>2</sub> emissions. Large-scale CO<sub>2</sub> sequestration options have not been proved and require R&D. Current commercial electrolyzers are 70-80% efficient, but the cost of hydrogen is strongly dependent on the cost of electricity. Production processes using wastes and biomass are under development, with a number of engineering scale-up projects underway.  
*Storage* - Liquid and compressed gas tanks are available and have been demonstrated in a small number of bus and automobile demonstration projects. Lightweight, fiber-wrapped tanks have been developed and tested for higher-pressure hydrogen storage. Experimental metal hydride tanks have been used in automobile demonstrations. Alternative solid-state storage systems using alanates and carbon nanotubes are under development.  
*Use* - Small demonstrations by domestic and foreign auto and bus companies have been undertaken. Small-scale power systems using fuel cells are being beta-tested. Small fuel cells for battery replacement applications have been developed. Much work remains.
- There have been important advances in storage energy densities in recent years: High-pressure composite tanks have been demonstrated with 7.5 wt.% storage capacity, exceeding the current DOE target, and new chemical hydrides have demonstrated a reversible capacity of 5 wt.% hydrogen. The composite tank development is a successful technology partnership among the national labs, DOE, and industry. Industrial investment in chemical hydride development recently has been initiated.
- SunLine Transit receives support to operate a variety of hydrogen production processes for its bus fleet. The California Fuel Cell Partnership has installed hydrogen refueling equipment (liquid delivered to the facility)
- Major industrial companies are pursuing R&D in fuel cells and hydrogen reformation technologies with a mid-term time frame for deployment of these technologies for both stationary and vehicular applications. These companies include:
 

ExxonMobil	Toyota
Shell	Daimler-Chrysler
Texaco	Honda
BP	International Fuel Cells
General Motors	Ballard
Ford	Air Products
Daimler-Chrysler	Praxair
Toyota	Plug Power Systems

### Technology History

- From the early 1800s to the mid-1900s, a gaseous product called town gas (manufactured from coal) supplied lighting and heating for America and Europe. Town gas is 50% hydrogen, with the rest comprised of mostly methane and carbon dioxide, with 3% to 6% carbon monoxide. Then, large natural gas fields were discovered, and networks of natural gas pipelines displaced town gas. (Town gas is still found in limited use today in Europe and Asia.)
- From 1958 to present, the National Aeronautics and Space Administration (NASA) has continued work on using hydrogen as a rocket fuel and electricity source via fuel cells. NASA became the worldwide largest user of liquid hydrogen and is renowned for its safe handling of hydrogen.
- During the 20th century, hydrogen was used extensively as a key component in the manufacture of

ammonia, methanol, gasoline, and heating oil. It was—and still is—also used to make fertilizers, glass, refined metals, vitamins, cosmetics, semiconductor circuits, soaps, lubricants, cleaners, margarine, and peanut butter.

- Recently, (in the late 20th century/dawn of 21st century) many industries worldwide have begun producing hydrogen, hydrogen-powered vehicles, hydrogen fuel cells, and other hydrogen products. From Japan's hydrogen delivery trucks to BMW's liquid-hydrogen passenger cars; to Ballard's fuel cell transit buses in Chicago and Vancouver, B.C.; to Palm Desert's Renewable Transportation Project; to Iceland's commitment to be the first hydrogen economy by 2030; to the forward-thinking work of many hydrogen organizations worldwide; to Hydrogen Now!'s public education work; the dynamic progress in Germany, Europe, Japan, Canada, the United States, Australia, Iceland, and several other countries launch hydrogen onto the main stage of the world's energy scene. Specific U.S.-based examples of hydrogen production and uses are as follows:

- A fully functional integrated renewable hydrogen utility system for the generation of hydrogen using concentrated solar power was demonstrated by cooperative project between industry and an Arizona utility company.

- A renewable energy fuel cell system in Reno, Nevada, produced hydrogen via electrolysis using intermittent renewable resources such as wind and solar energy.

- An industry-led project has developed fueling systems for small fleets and home refueling of passenger vehicles. The refueling systems deliver gaseous hydrogen up to 5,000 psi to the vehicle. A transit agency in California installed an autothermal reformer, generating hydrogen for buses and other vehicles. This facility also operates a PV-powered electrolysis system to provide renewable hydrogen to their fleet.

### **Technology Future**

- Fuel cells are a promising technology for use as a source of heat and electricity for buildings, and as an electrical power source for electric vehicles. Although these applications would ideally run off pure hydrogen, in the near-term they are likely to be fueled with natural gas, methanol, or even gasoline. Reforming these fuels to create hydrogen will allow the use of much of our current energy infrastructure—gas stations, natural gas pipelines, etc.—while fuel cells are phased in. The electricity grid and the natural gas pipeline system will serve to supply primary energy to hydrogen producers.

- By 2005, if DOE R&D goals are met, (1) onboard hydrogen storage in metal hydrides at >5 wt% will be developed; (2) complete engineering design of a small-scale, mass-producible reformer for natural gas will be completed; and (3) an integrated biomass-to-hydrogen system will be demonstrated.

- By 2010, advances will be made in photobiological and photoelectrochemical processes for hydrogen production, efficiencies of fuel cells for electric power generation will increase, and advances will be made in fuel cell systems based on carbon structures, alanates, and metal hydrides. The RD&D target for 2010 is \$45/kW for internal combustion engines operating on hydrogen; the cost goal is \$30/kW by 2015.

- Although comparatively little hydrogen is currently used as fuel or as an energy carrier, the long-term potential is for us to make a transition to a hydrogen-based economy in which hydrogen will join electricity as a major energy carrier. Furthermore, much of the hydrogen will be derived from domestically plentiful renewable energy or fossil resources, making the Hydrogen Economy synonymous with sustainable development and energy security.

- In summary, future fuel cell technology will be characterized by reduced costs and increased reliability for transportation and stationary (power) applications.

- To enable the transition to a hydrogen economy, the cost of hydrogen energy is targeted to be equivalent to gasoline market prices (\$1.50/gallon in 2001 dollars).

- For a fully developed hydrogen energy system, a new hydrogen infrastructure/delivery system will be required.

- In the future, hydrogen also could join electricity as an important *energy carrier*. An energy carrier stores, moves, and delivers energy in a usable form to consumers. Renewable energy sources, such as the sun or wind, can't produce energy all the time. The sun doesn't always shine nor the wind blow. But hydrogen can store this energy until it is needed and it can be transported to where it is needed.
- Some experts think that hydrogen will form the basic energy infrastructure that will power future societies, replacing today's natural gas, oil, coal, and electricity infrastructures. They see a new *hydrogen economy* to replace our current energy economies, although that vision probably won't happen until far in the future.

**Sources:** National Renewable Energy Laboratory. *U.S. Climate Change Technology Program. Technology Options: For the Near and Long Term*. DOE/PI-0002. November 2003; and National Renewable Energy Laboratory. *Gas-Fired Distributed Energy Resource Technology Characterizations*. NREL/TP-620/34783. November 2003.